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TECHNICAL NOTE 4310

MEASUREMENTS OF THE MOTIONS OF A LARGE SWEPT-WING AIRPLANE IN ROUGH AIR

By Richard H. Rhyne

Langley Aeronautical Laboratory
Langley Field, Va.

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SUMMARY

Flight test measurements of the angular and linear motions of a large swept-wing airplane in rough air are presented for altitudes of 5,000 and 35,000 feet. These measurements are summarized in the form of power spectra, root-mean-square values, and probability distributions. Examination of these results indicates the predominance of the Dutch roll and short-period pitching modes on the lateral and longitudinal motions in rough air. Brief consideration is also given to the problem of extrapolating the present results to other turbulence conditions.

INTRODUCTION

The magnitude and frequency content of the random-type motions of airplanes in rough air are of considerable interest in connection with the development of ground and airborne tracking systems, the design of internal equipment of the airplane, such as navigation, interception, bombing, or collision warning systems, and the study of aeromedicine. Although these motions may be calculated on the basis of available information on atmospheric turbulence and use of the airplane equations of motion (refs. 1 and 2), the reliability of such calculations has not been well established. Thus, there exists an interest in the direct measurements of airplane motions in rough air. Little information of this type appears to be available in published literature.

The present paper summarizes measurements of the angular and linear motions of a large swept-wing airplane in rough air. The measurements were obtained in connection with an investigation of the loads and strain responses of the airplane. (See ref. 3.) In addition, characteristics of the turbulence encountered were determined with the use of the angle-of-attack vane-measuring technique of reference 4. Data are presented in the form of sample time histories of the airplane displacements, velocities, and accelerations, as well as power spectra, root-mean-square values, and probability distributions of the various measured quantities. The problem of extrapolating the measurements to other turbulence conditions is also considered briefly.

SYMBOLS

f	frequency, cps
g	acceleration due to gravity, 32.2 ft/sec^2
L	scale of turbulence, ft
T	specified time
t	time, sec
w_g	vertical gust velocity, ft/sec
$y(t)$	random function of time
λ	gust wavelength, ft
σ	root-mean-square deviation
σ_U	root-mean-square gust velocity
σ_{Um}	measured root-mean-square gust velocity
$\Phi(f)$	power-spectral-density function, $\lim\limits_{T\to\infty} \frac{1}{T}\left\|\int_{-T}^{T} y(t)e^{-i2\pi ft}dt\right\|^2$
$\Phi_{ext}(f)$	extrapolated response spectrum
$\Phi_m(f)$	measured response spectrum
Ω	reduced frequency, $2\pi/\lambda$, radians/ft

AIRPLANE AND INSTRUMENTATION

A photograph of the test airplane is shown in figure 1, and a three-view sketch showing the location of the pertinent instrumentation is given in figure 2. The only changes in the external configuration of the standard airplane were the addition of a nose boom, which was used for measuring airspeed and which also served as a mount for the angle-of-attack vane, and an external canopy mounted on top of the fuselage to house some of the instruments. (See figs. 1 and 2.) Pertinent physical characteristics and dimensions of the test airplane are given in table I.

Instrumentation utilized in the present investigation consisted of the following:

(1) An NACA air-damped recording accelerometer (frequency response, flat to at least 5 cps; accuracy, ±0.0125g) mounted within 2 feet of the airplane center of gravity to measure normal acceleration.

(2) An NACA air-damped recording accelerometer (with frequency response and accuracy approximately the same as above) mounted within 2 feet of the airplane center of gravity and oriented so as to measure lateral acceleration.

(3) An NACA oil-damped accelerometer (response, flat to about 10 cps; accuracy, ±0.02g) located on the left wing tip at the rear spar (as shown in fig. 2) to measure normal acceleration.

(4) An angle-of-attack vane mounted on the boom approximately 6.5 feet ahead of the nose and 52.5 feet ahead of the airplane center of gravity to measure incremental angle of attack. (Frequency response for the present test conditions was limited by the recording element, which had a natural frequency of about 10 cps and a damping ratio of about 0.7.)

(5) An NACA airspeed-altitude recorder to record airspeed and pressure altitude.

(6) Magnetically damped NACA turnmeters located within 2 feet of the airplane center of gravity (as shown in fig. 2) to measure pitching, rolling, and yawing velocities. (These turnmeters had natural frequencies of about 6.7 cps and damping ratios of about 0.67.)

(7) NACA attitude recorders located within 2 feet of the airplane center of gravity (as shown in fig. 2) to record pitch, roll, and yaw attitude.

(8) NACA resistance-type control-position recorders to record the aileron, rudder, and elevator displacements. (These records were monitored to provide an indication of any pilot-induced airplane motions.)

The film speed of the recorders was approximately 1/4 inch per second, and all recorders were correlated by means of an NACA 1/10-second chronometric timer.

In addition to the recording instruments, cameras operating at a speed of 1 frame every 2 seconds photographed the fuel gages in order to determine the airplane weight at any point during the flight.

TESTS AND SCOPE OF DATA

The present data were obtained from two tests in continuous clear-air turbulence. The first test had a duration of 4 minutes and covered approximately 30 miles at an altitude of 5,000 feet. The flight Mach number was 0.63 and the dynamic pressure was 484 lb/sq ft. The second test of about $1\frac{1}{2}$ minutes was made at an altitude of about 35,000 feet. The test covered a distance of about 10 miles at a flight Mach number of 0.64 and a dynamic pressure of 145 lb/sq ft. The level of turbulence for both tests may be classified as "light."

The average airplane weight for the tests at an altitude of 5,000 feet was 113,000 pounds and at 35,000 feet was 112,000 pounds. The center of gravity was located at about 20 percent mean aerodynamic chord. The airplane was flown with the yaw damper off, and both tests were made with "hands-off" control; that is, minor deviations of the airplane from the prescribed altitude and heading were not corrected by the pilot, and large deviations were corrected only by gradual control movements. This procedure results in the controls being essentially "fixed" due to the irreversible power-boost control system employed in the test airplane.

EVALUATION OF DATA AND RESULTS

Time Histories

The basic measurements utilized in this study were the time-history records of the angular velocity, the normal and lateral accelerations, and the airplane angle of attack. These time histories were also used to obtain additional quantities in the following manner:

(a) The angular velocities in pitch and yaw were utilized to obtain angular-displacement time histories (due to malfunction of the pitch and yaw attitude recorders).

(b) The accelerations were used to determine linear velocities and displacements.

(c) Airplane angle of attack, pitching velocity, pitch attitude, and airplane vertical velocity, together with airspeed, were utilized in determining a time history of gust velocity in accordance with the procedure of reference 4.

In almost all cases, examination of the records indicated that the motions occurred at frequencies below 5 cps. The basic reading interval used was therefore 0.1 second. (Preliminary indications were that the normal acceleration measured at the wing tip contained higher frequencies; and, therefore, this time history was read at 0.05-second intervals. The center-of-gravity acceleration was also read at an interval of 0.05 second to increase the accuracy of a double integration performed on this time history.)

In order to show the characteristics of the various quantities, sample time histories for an altitude of 5,000 feet are presented in figure 3. Figure 3(a) shows time histories of the angular velocities and attitudes of the airplane about the three axes. The angular velocities in roll and yaw are seen to consist largely of motions associated with the airplane Dutch roll mode, with a predominant frequency of approximately 1/4 cps (period of 4 seconds). The pitching velocity is seen to have a predominant frequency of about 1/2 cps (period of 2 seconds), which is the airplane's short-period pitching mode frequency. The airplane-attitude time histories evidence a very slow long-period motion in addition to containing the higher frequencies just mentioned for the angular velocities. From examination of the complete time histories, these slow attitude changes appear to have a period of greater than 100 seconds; and, in the case of the roll attitude, inspection of the control-position records indicates that there is considerable influence of gradual aileron movement by the pilot.

The measured and derived time histories presented in figure 3(b) consist of normal and lateral acceleration at the airplane center of gravity and normal acceleration at the wing tip together with the various quantities necessary in the determination of the input vertical gust velocity. The airplane vertical velocity was obtained by integrating the time history of normal acceleration at the center of gravity, and the airplane vertical displacement was obtained by integrating the airplane vertical velocity. The double integration of the normal acceleration at the center of gravity was checked against the recording of pressure altitude, and adjustments were made to the initial values of the vertical velocity to make this second integration conform to the incremental change in the pressure altitude. As indicated previously, the gust velocity was derived from the measurements of the angle of attack, airspeed, and the airplane pitching and vertical motions in accordance with the procedure of reference 4. These time histories, in general, contain the same predominant frequencies as the time histories of the angular motions presented in figure 3(a), with the acceleration time histories showing, in addition, some higher frequencies. For the time history of wing-tip normal acceleration, in particular, the wing-first-bending frequency $\left(\text{about } 1\frac{1}{2} \text{ cps}\right)$ is clearly evident.

Power Spectra and Root-Mean-Square Values

Power spectra of the various measured quantities were determined by using the method of reference 5. These power spectra are presented in figures 4 to 6. Generally, the spectra were obtained by using 60 lags and a reading interval of 0.1 second. Sixty power estimates over the frequency range from 0 to 5 cps thereby resulted. (Actually, as a result of the 0.05-second reading interval, the spectra of wing-tip acceleration and center-of-gravity acceleration for the low altitude were obtained to a frequency of 10 cps; but, since they contained only small power at the higher frequencies, they are shown only to a frequency of 5 cps.) The spectrum of gust velocity was not considered to be reliable at frequencies below 1/4 cps because of the magnification of the reading error by the double integration of the center-of-gravity acceleration, or above 3 cps because of the vibration of the boom on which the angle-of-attack vane was mounted; therefore, the spectrum is not shown beyond these limits. The root-mean-square values for the various measurements are given in table II and are also given in figures 4 to 6.

Figure 4 presents the spectrum of gust velocity for the low-altitude tests (5,000 feet). A spectrum of gust velocity for the high-altitude tests (35,000 feet) is not presented because of difficulty in obtaining a reliable time history of angle of attack at the high altitude. This difficulty arose as a result of excessive vibration of the boom on which the angle-of-attack vane was mounted. Figure 4 also includes a calculated spectrum (dashed line) which is discussed subsequently. Reference 6, which presents data obtained from tests that are the same as those utilized in the present investigation, indicates that the level of turbulence for the tests at altitudes of 5,000 and 35,000 feet was roughly the same in terms of true gust velocity. When compared with data summarized in reference 7, the level of turbulence for the two altitudes would be classified as "light," as noted previously.

Figure 5 presents power spectra of the angular velocities of the airplane about the three axes for the two altitudes. Examination of the spectra indicates that most of the power is concentrated at frequencies below 1 cps, with the amplitude of the rolling velocities being the largest, the yawing velocities somewhat smaller, and the pitching velocities even lower. The same relative magnitudes are seen to exist for the root-mean-square values. It might also be noted that rolling and yawing velocities are larger for the tests at an altitude of 35,000 feet than for those at an altitude of 5,000 feet, whereas pitching velocities are roughly the same for the two altitudes. Secondary power peaks occur in the pitching-velocity spectra at a frequency of about 1.3 cps and are attributed to a coupling between the wing-bending and airplane-pitching modes. A peak is also present at a frequency slightly above 2 cps in the rolling-velocity spectrum for an altitude of 35,000 feet and is attributed to an unsymmetrical wing-bending mode.

The power spectra of the normal and lateral accelerations presented in figure 6 contain power peaks at approximately the same frequencies as the spectra of the longitudinal and lateral angular velocities. The magnitude of the root-mean-square values for both the normal and lateral accelerations are greater at the low altitude than at the high altitude. The predominant peak in the normal-acceleration spectrum is also higher for the low-altitude tests. For the lateral-acceleration spectra, however, the predominant peak is slightly higher for the tests at 35,000 feet. (The lateral-acceleration time histories are influenced somewhat by the large roll angles attained by the airplane, particularly for the tests at 35,000 feet; the large roll angles thus possibly account for the higher peak in this particular spectrum.) The very large peak in the spectrum of normal acceleration for the wing tip at a frequency of approximately 1.6 cps is attributed to the fundamental wing-bending mode. Because of the very flexible wing of the test airplane, the root-mean-square value for the wing-tip normal accelerations is also rather large.

Probability Distributions

In order to show the maximum magnitudes reached and the proportion of flight time spent at different amplitude levels, probability distributions of the angular velocities and linear accelerations are presented in figures 7 and 8, respectively. In view of the interest in the degree to which these observed distributions approximate a Gaussian distribution, probability paper was used for the plots. This paper is scaled in a manner that yields a straight line for a Gaussian probability distribution. The data in the figures, termed "probability of exceeding," are plotted in terms of proportion of total readings above given levels (or of total flight time since the readings are at equally spaced intervals of 0.1 second). For this purpose, the data were first grouped into suitable class intervals according to magnitude. From the class intervals, the average probability of exceeding given values of x, $P(x)$, was determined by the following relation:

$$P(x) = \frac{n(x)}{N} \tag{1}$$

where $n(x)$ is the number of values exceeding a given value of x from the tabulated class intervals, and N is the total number of values.

Inspection of the probability distributions of angular velocity (fig. 7) shows that the rolling velocities attained for the tests at an altitude of 35,000 feet were considerably larger than the other motions. For these rolling motions, the plot shows that approximately 10 percent of the time is spent below -0.08 radian/sec (i.e., in the negative direction or rolling to the left). Similarly, approximately 10 percent of the time is spent above +0.08 radian/sec (rolling to the right). In other words, 80 percent of the time is spent at rolling velocities between ±0.08 radian/sec. For yawing and pitching velocities at an altitude of 35,000 feet, the yawing velocities are above 0.03 radian/sec (or below -0.03 radian/sec) for 10 percent of the time, and the pitching velocities are above 0.01 radian/sec (or below -0.01 radian/sec) for 10 percent of the time. The values for the tests at 5,000 feet are smaller for the rolling and yawing velocities and are about the same for the pitching velocity.

Figure 8, which presents the probability distributions of the normal and lateral accelerations for the two altitudes, shows the accelerations to be larger for the low-altitude tests. For 10 percent of the time, the normal accelerations are above 4 ft/sec^2 (or below -4 ft/sec^2) for the low-altitude tests and above approximately 2 ft/sec^2 for the high-altitude tests. The lateral accelerations are about the same for both altitudes, being above approximately 1 ft/sec^2 for 10 percent of the time.

From comparison with the fitted normal distribution (solid- and dashed-line curves), all the measured distribution data of figures 7 and 8 are seen to approximate a Gaussian probability distribution. Reference 8 considers briefly the degree to which a Gaussian distribution is approximated by a specific 4-minute turbulence sample (also used in the present test) and indicates that the measured distribution of gust velocity approximates a Gaussian distribution quite well, although some discrepancy is evident. The significance of these departures from a Gaussian distribution would appear to depend on the application.

Extrapolations to Other Turbulence Conditions

The present results on the airplane motions were obtained under a specific set of turbulence conditions - in particular, under conditions that might be considered as relatively light turbulence. It is of interest to consider how these results might be extrapolated to other turbulence conditions. For this purpose, it will be helpful to obtain an analytic representation of the turbulence spectrum (fig. 4) measured for the vertical component of turbulence in the present tests. The following expression for the spectrum of atmospheric turbulence has been found to be a useful interpolation formula for the spectra of atmospheric turbulence in other investigations (for example, ref. 7):

$$\Phi(\Omega) = \sigma_U^2 \frac{L}{\pi} \frac{1 + 3\Omega^2 L^2}{\left(1 + \Omega^2 L^2\right)^2} \tag{2}$$

where σ_U is the root-mean-square gust velocity, L is the scale of turbulence, $\Omega = 2\pi/\lambda$, and λ is the gust wavelength. The dashed curve shown in figure 4 represents a fitted curve having this prescribed spectrum with a value of 1,000 feet for the scale of turbulence L. The root-mean-square gust velocity for the fitted curve is 3.0 ft/sec and will be designated σ_{Um}.

For other conditions of atmospheric-turbulence intensity (but having the same spectral form), it may be expected from linear theory (see ref. 5) that the spectrum of the extrapolated response $\Phi_{ext}(f)$ will be directly proportional to σ_U^2 as given by the following expression:

$$\Phi_{ext}(f) = \frac{\sigma_U^2}{\sigma_{Um}^2} \Phi_m(f) \tag{3}$$

where σ_U is the root-mean-square gust velocity for other turbulence conditions and $\Phi_m(f)$ is the measured spectrum obtained in the present investigation for the corresponding response. A similar procedure would also appear to be applicable for the lateral responses if it is assumed that the power spectra of the lateral and vertical components of the turbulence have a direct relationship (for example, equivalent for isotropic turbulence).

The probability distributions for the various response motions may likewise be extrapolated linearly. The probability distributions for the expected motions in turbulence of other intensities are given by the following expression:

$$P_{ext}(x) = P_m\left(\frac{\sigma_{Um}}{\sigma_U} x\right) \tag{4}$$

where $P_{ext}(\ )$ is the extrapolated probability distribution, $P_m(\ )$ is the measured probability distribution in the present investigation, and x is the response quantity of interest.

Extrapolation of the present results to other airplanes is perhaps also possible. Such extrapolations would, however, require detailed analysis of the response characteristics of both the present airplane and the prospective airplane along the lines considered in reference 7.

CONCLUDING REMARKS

Flight tests were made on a large swept-wing airplane at altitudes of 5,000 and 35,000 feet. Results indicate that under conditions of light rough air, the Dutch roll frequencies (about 1/4 cps) were predominant in the lateral motions whereas the short-period pitching frequencies (approximately 1/2 cps) were predominant in the longitudinal motions. The probability distributions obtained for the various measured quantities were all approximately Gaussian. A simple procedure is given for extrapolating the measurements of the probability distributions and the power spectra to other turbulence conditions.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., August 25, 1958.

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TABLE I

PERTINENT PHYSICAL CHARACTERISTICS AND

DIMENSIONS OF THE TEST AIRPLANE

Total wing area, sq ft	1,428
Wing span, ft	116
Wing aspect ratio	9.43
Wing thickness ratio	0.12
Wing taper ratio	0.42
Wing mean aerodynamic chord, in.	155.9
Wing sweepback (25-percent-chord line), deg	35
Total horizontal-tail area, sq ft	268
Horizontal-tail span, ft	33
Horizontal-tail mean aerodynamic chord, in.	102.9
Horizontal-tail sweepback (25-percent-chord line), deg	35
Airplane weight, lb -	
At 5,000 feet	113,000
At 35,000 feet	112,000
Center of gravity, percent M.A.C.	20.0

TABLE II

ROOT-MEAN-SQUARE VALUES FOR VARIOUS MEASUREMENTS

Measurement	Root-mean square values at -	
	5,000 ft	35,000 ft
Pitching velocity, radians/sec	0.0078	0.0067
Rolling velocity, radians/sec	0.0205	0.0578
Yawing velocity, radians/sec	0.0090	0.0212
Normal acceleration at c.g., ft/sec^2	3.43	1.94
Normal acceleration at wing tip, ft/sec^2	16.58	------
Lateral acceleration at c.g., ft/sec^2	1.12	0.90
Gust velocity, ft/sec	3.0	------

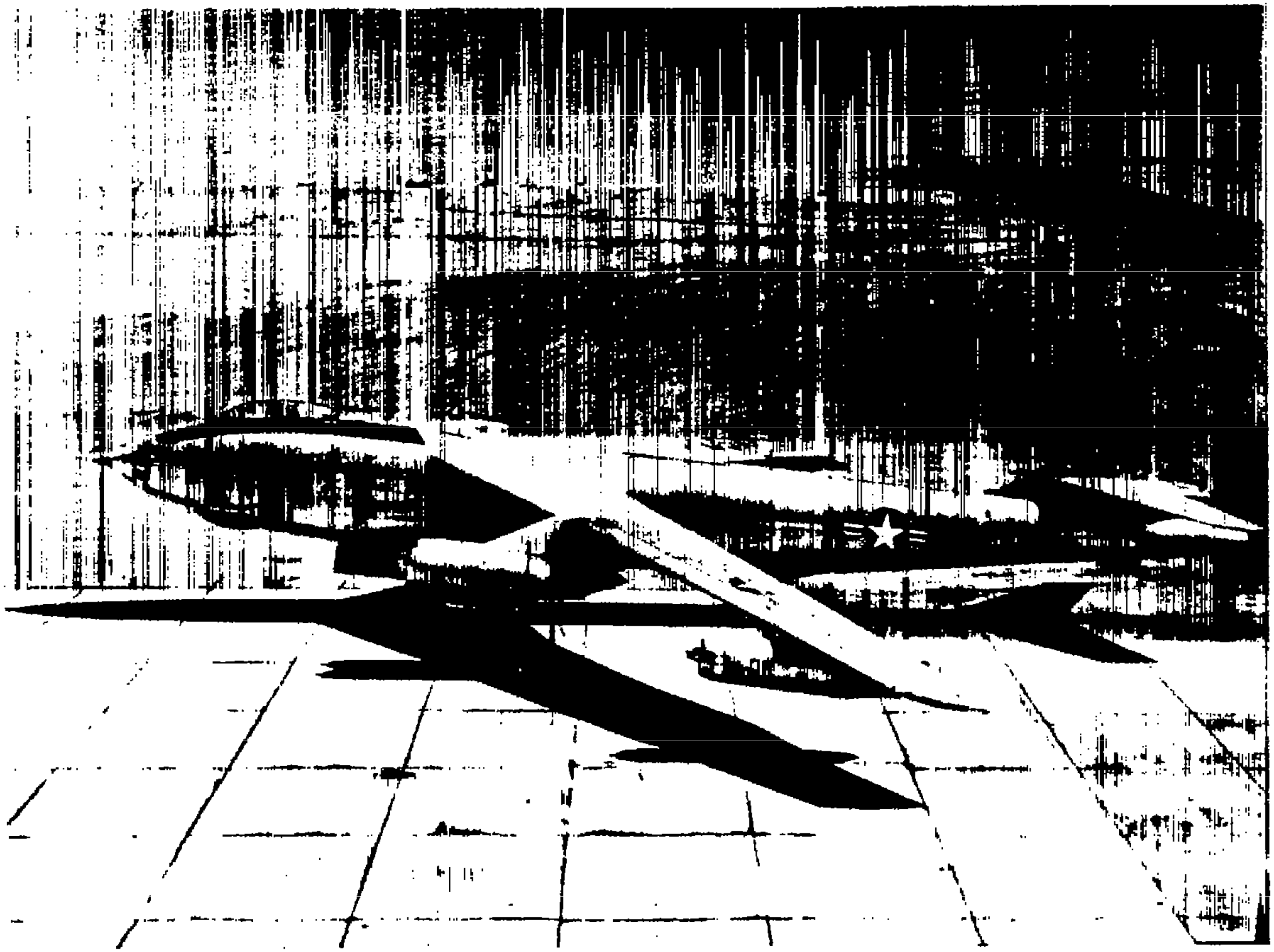


Figure 1.- Photograph of test airplane. L-86692

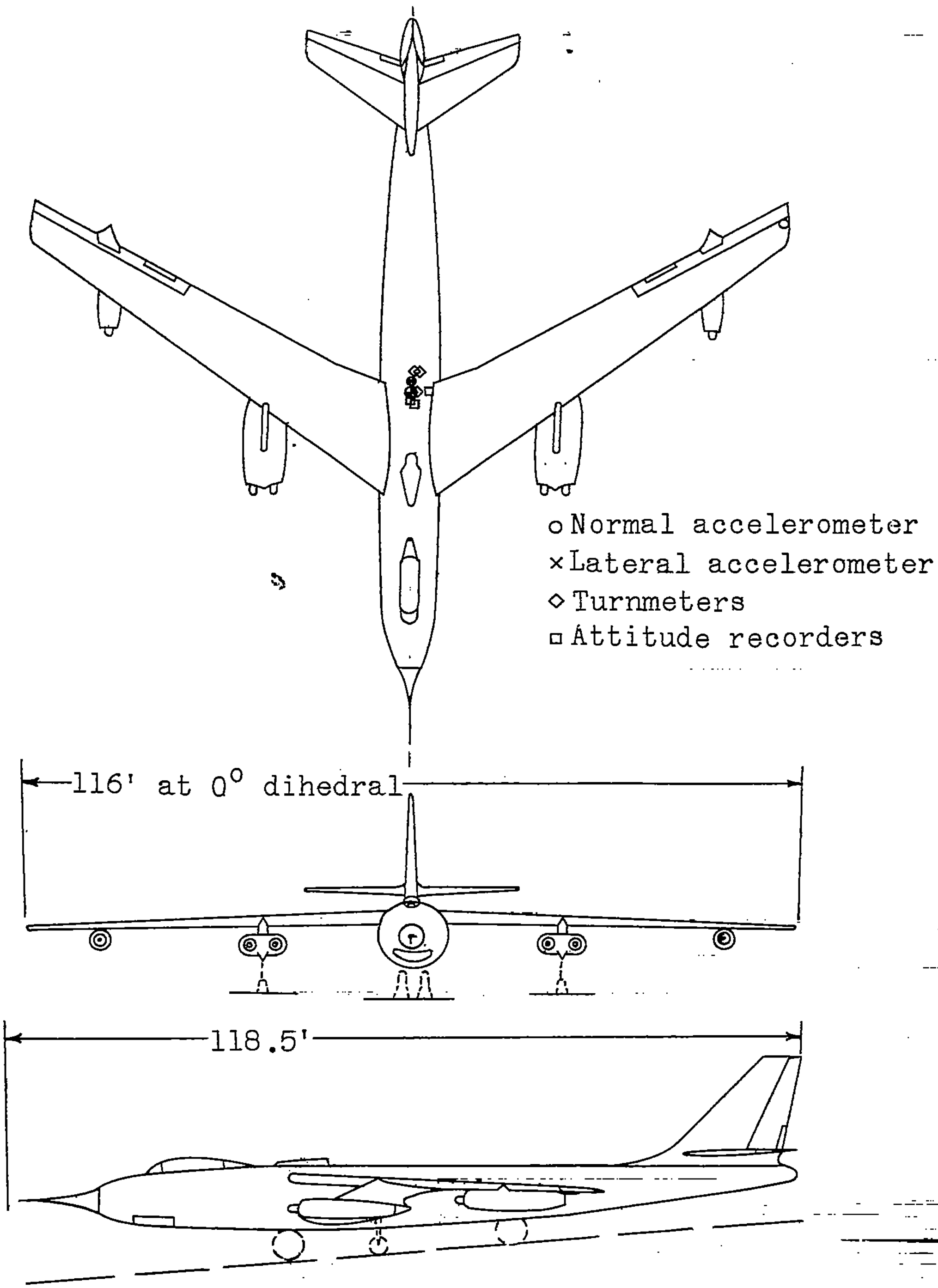
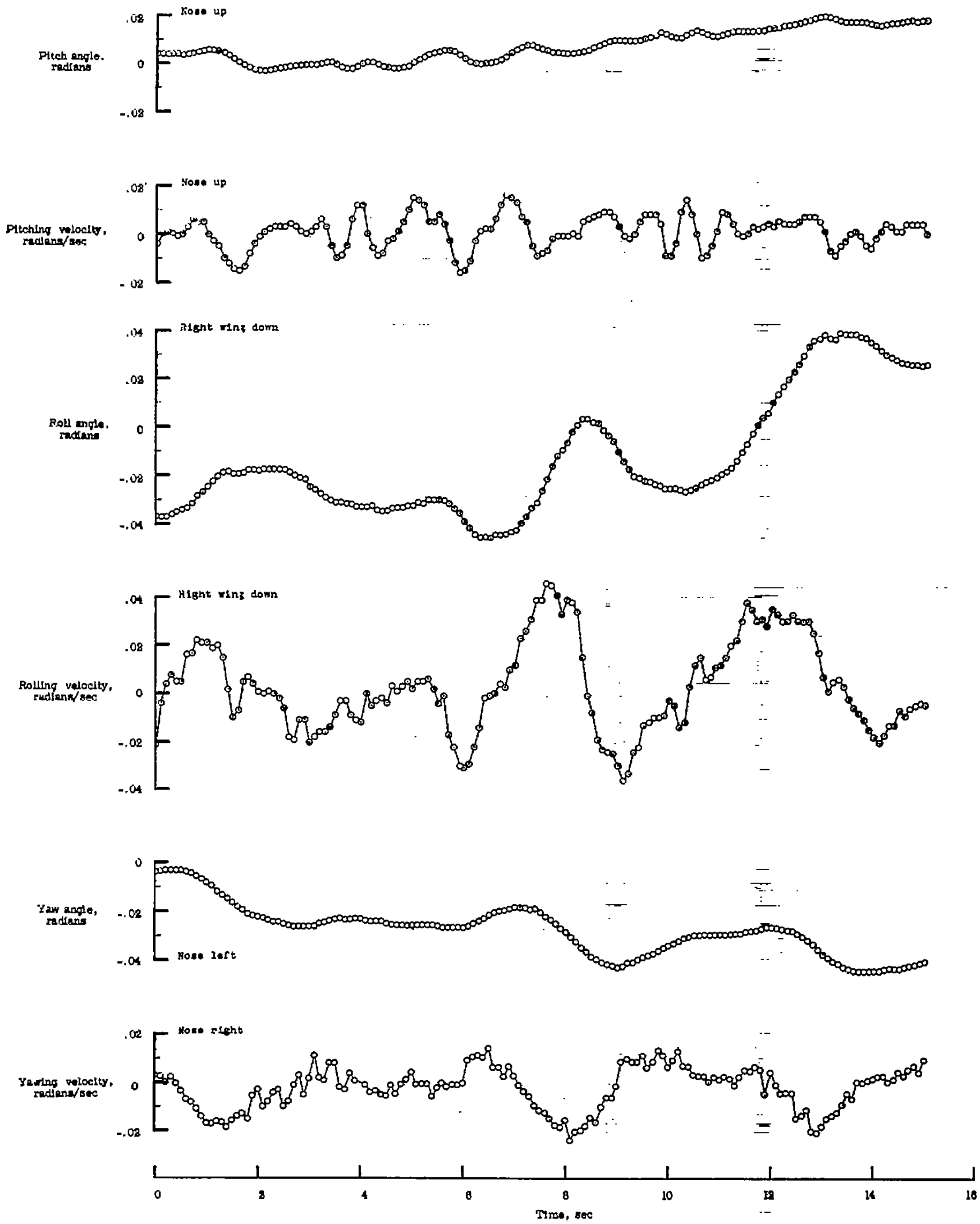
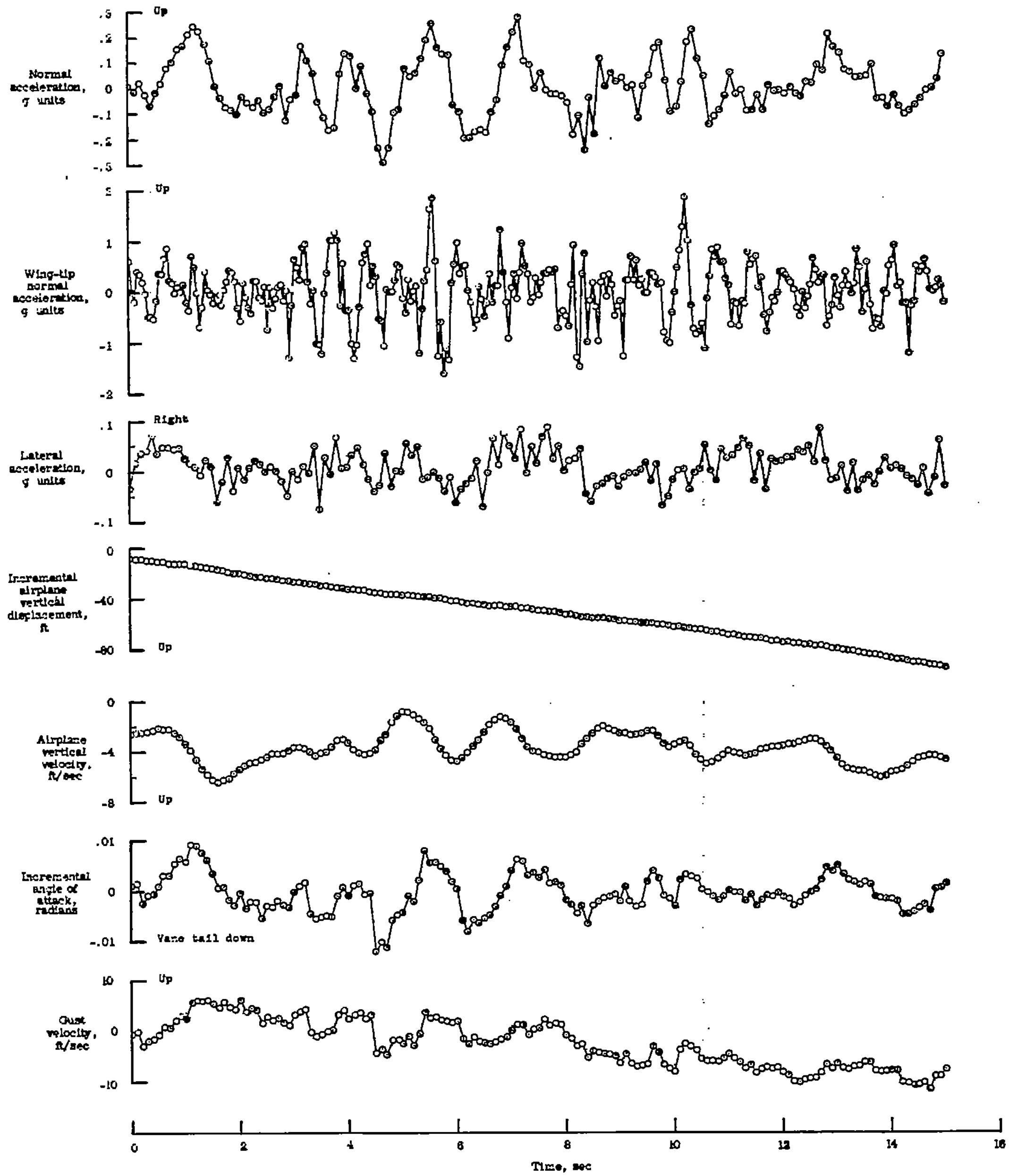


Figure 2.- Three-view drawing of test airplane.



(a) Angular displacements and velocities.

Figure 3.- Sample time histories for altitude of 5,000 feet.



(b) Linear accelerations, displacements, and velocities.

Figure 3.- Concluded.

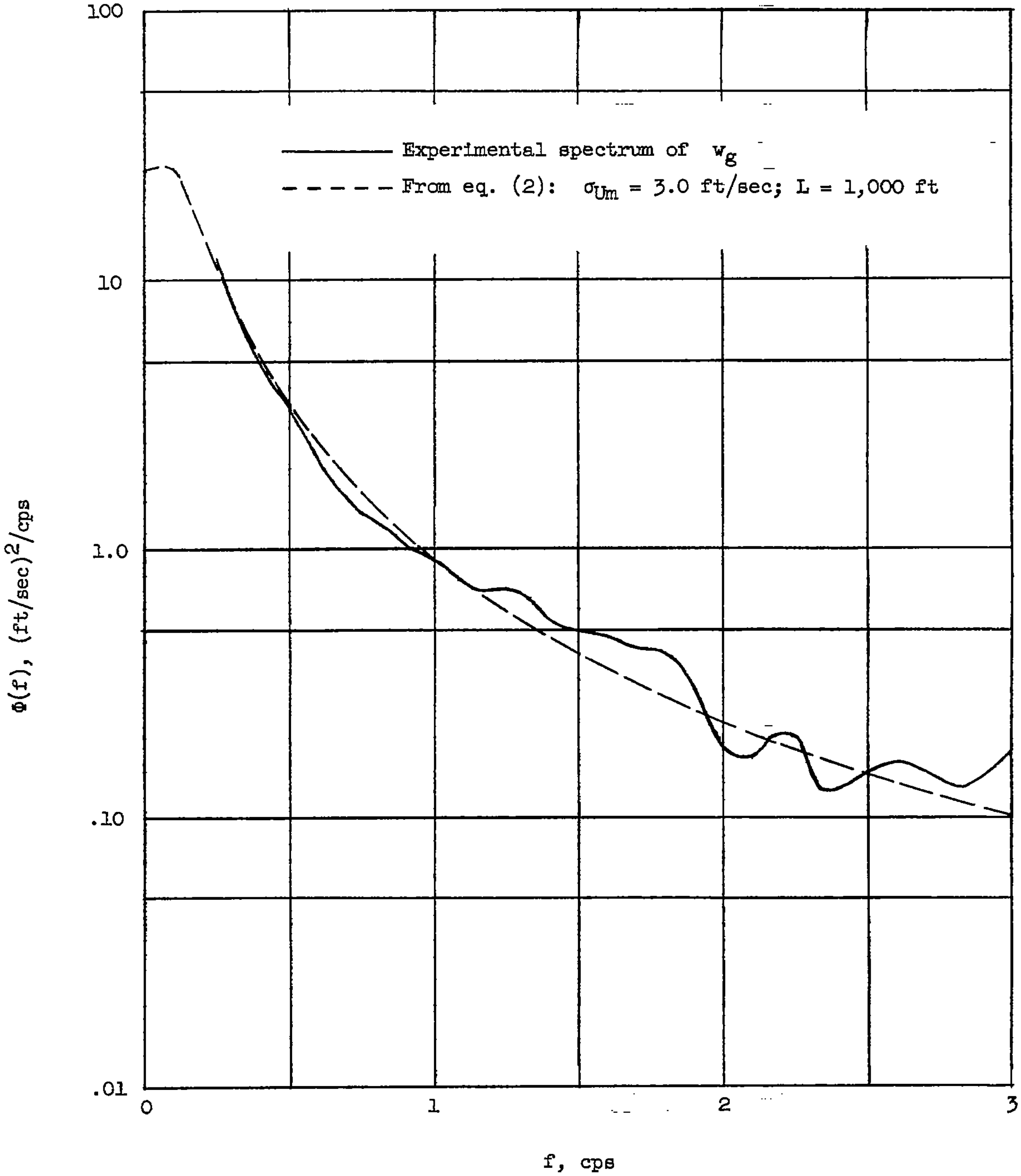


Figure 4.- Power spectrum of vertical gust velocity for altitude of 5,000 feet.

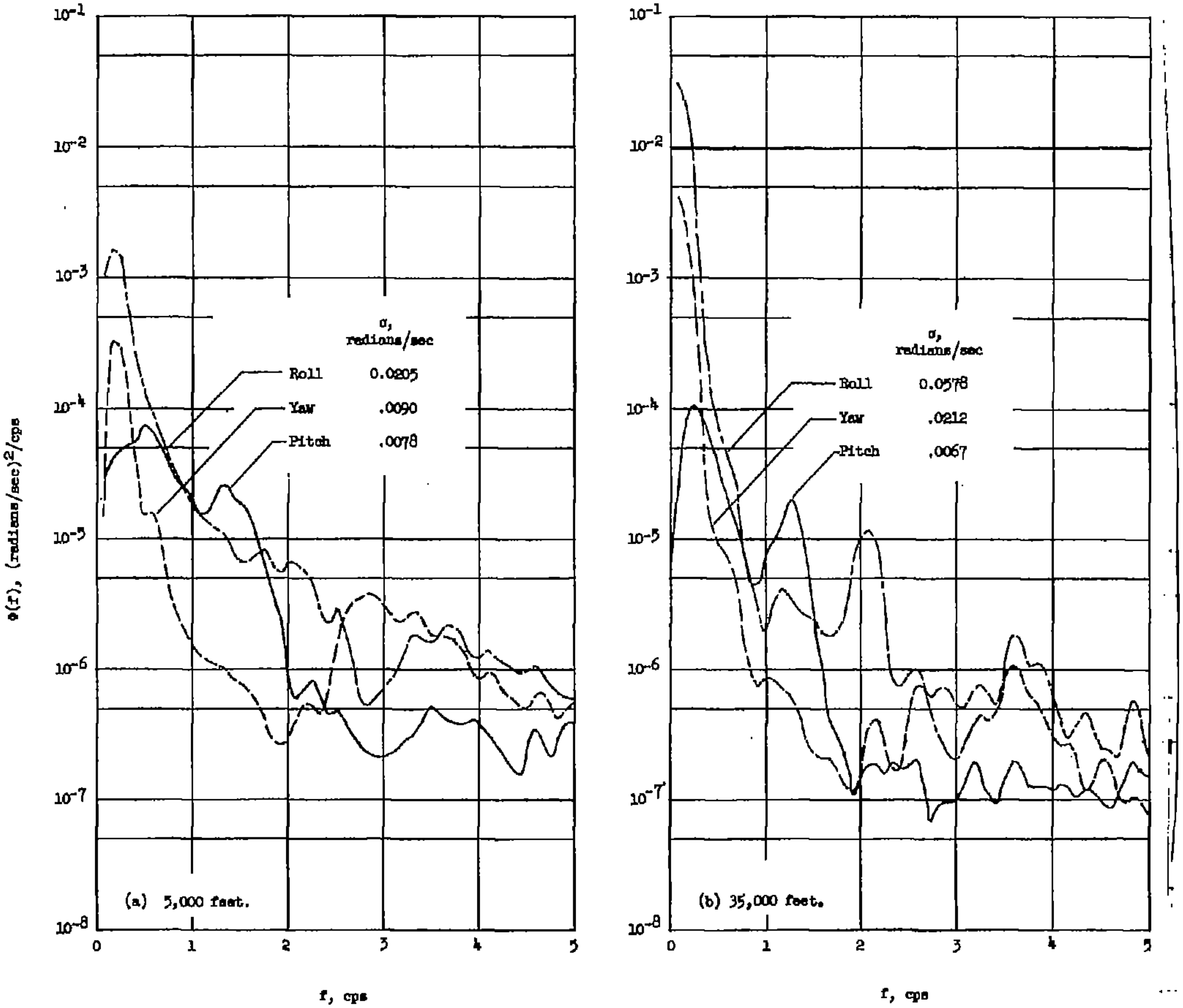


Figure 5.- Power spectra of angular velocities.

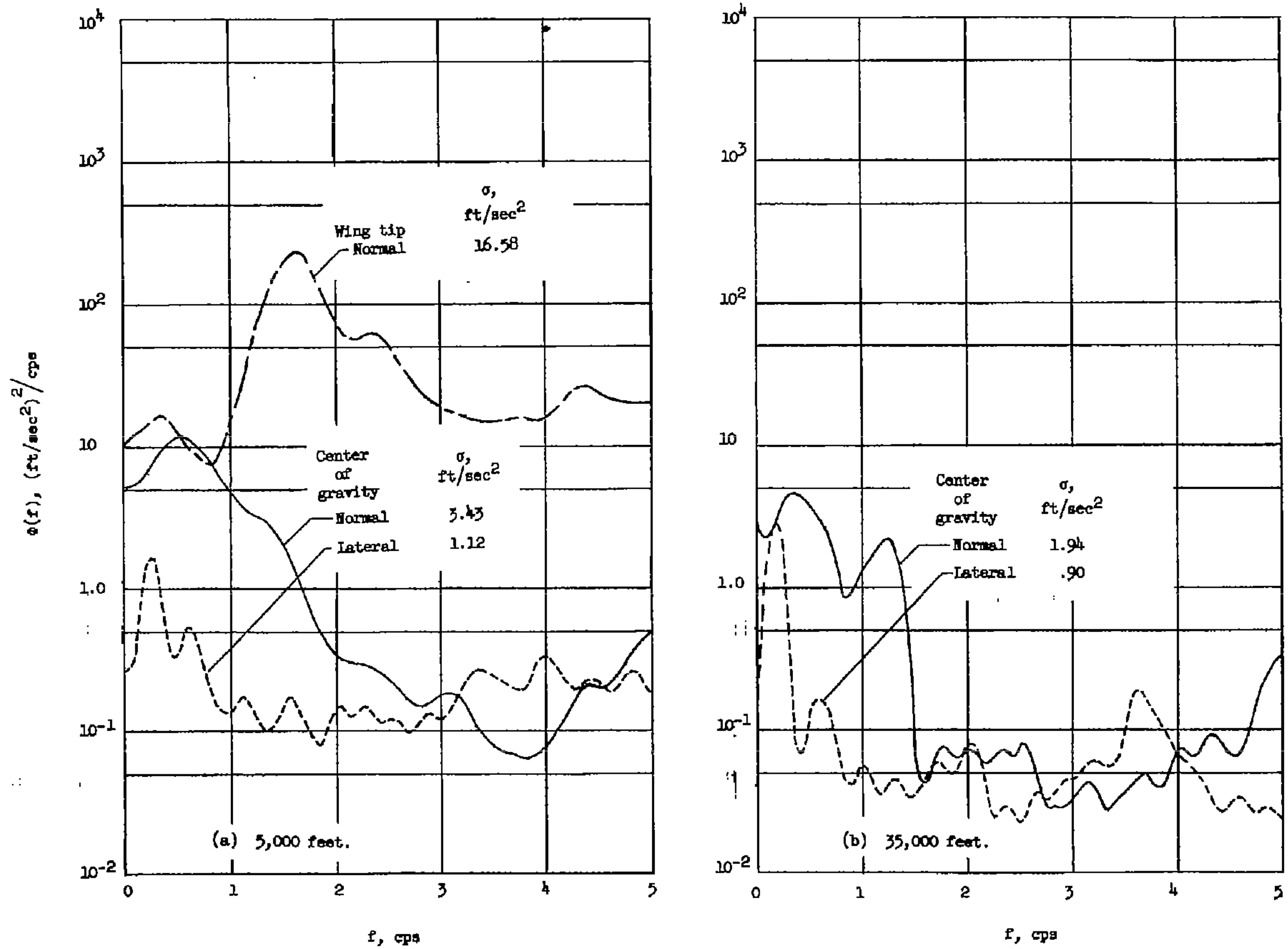


Figure 6.- Power spectra of accelerations.

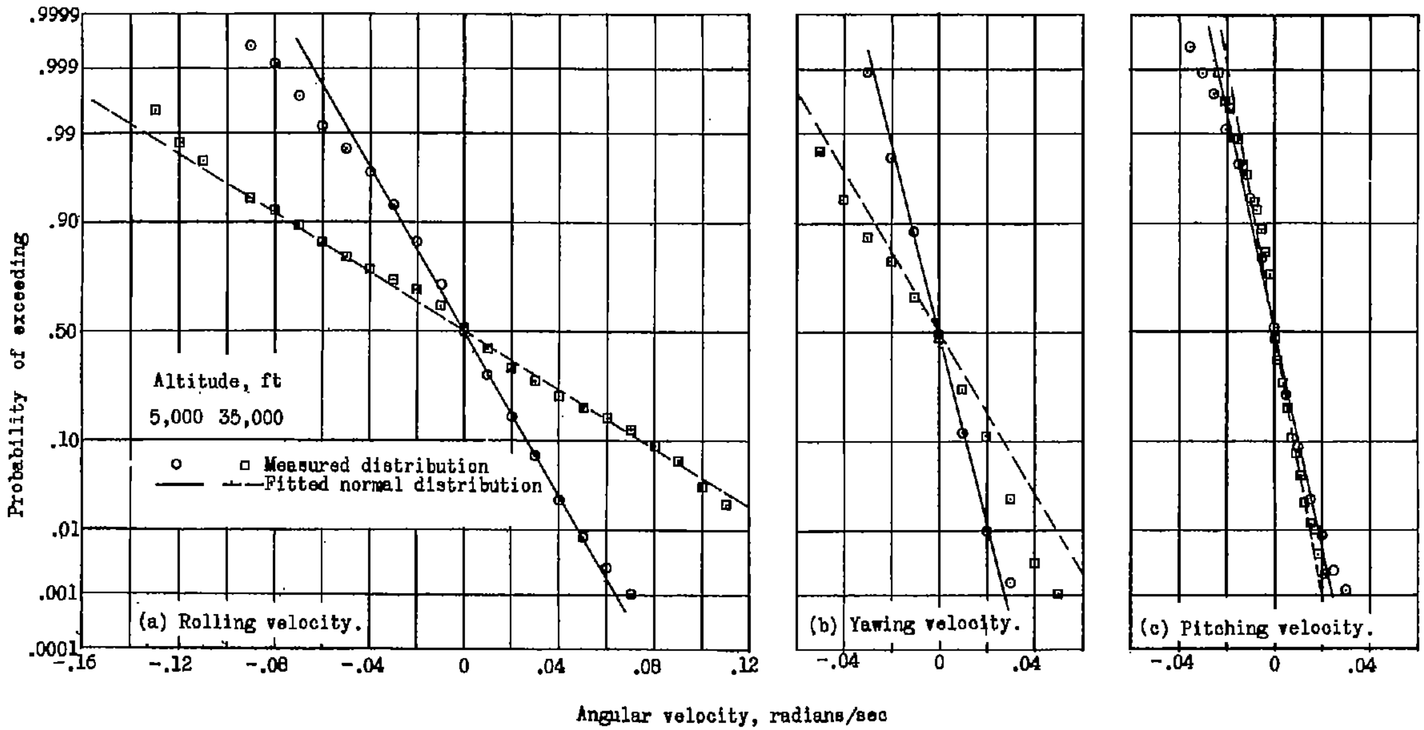


Figure 7.- Probability of equaling or exceeding given values of angular velocity.

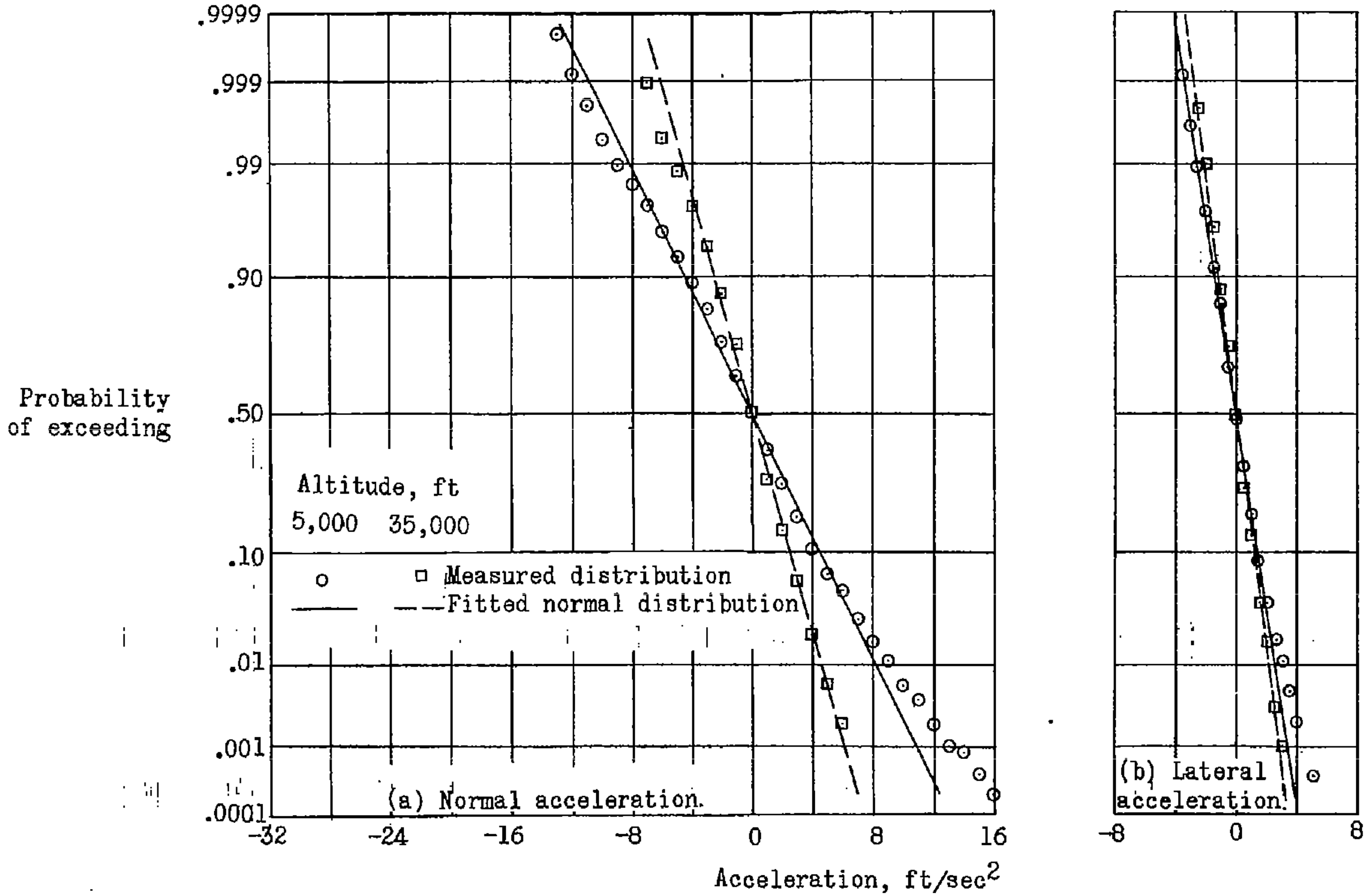


Figure 8.- Probability of equaling or exceeding given values of acceleration at the center of gravity.

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